EMISSION MECHANISMS IN X-RAY SOURCES

(Invited Discourse)

L. WOLTJER
Dept. of Astronomy, Columbia University, New York, N.Y., U.S.A.

1. Introduction

A large body of spectral information on X-ray sources has now become available, but the interpretation remains ambiguous. If temperature variations and finite optical depth effects are taken into account, almost any spectrum can be fitted to a model of thermal bremsstrahlung. If a suitable energy spectrum is adopted for the relativistic electrons, a wide variety of synchrotron spectra becomes possible. Although one or the other interpretation may seem artificial in some cases, it nevertheless should be pointed out that a strictly isothermal source would be a miracle and that power-law type energy spectra of the relativistic particles can apply over only a limited range of energies. More satisfactory progress can be made when the spectral data are augmented with structural information, when emission lines can be studied and polarization can be measured. Not only do the intensities of emission lines give much more detailed information on the temperature and density in a hot gas than can be derived from the continuum, but at sufficient resolution velocity fields can also be studied. Useful structural information probably can be obtained only if spatial resolution of 1 arc-min or better is achieved. But one has only to look at the situation in radio astronomy to see how essential this information is for the building of quantitative models.

For the near future polarization data are vital for separating thermal and non-thermal radiation, although the situation is not as unambiguous as might have been hoped on account of the possible effects of electron scattering in asymmetrical thermal sources (Angel, 1969). But again, a combination with high spatial resolution is required to profit in full from the polarization information.

In the following we shall review the various processes that have been discussed as possible mechanisms for the X-ray emission in galactic sources.

2. Black-Body Emission

Immediately after the discovery of the first X-ray sources it was realized that a neutron star with a surface temperature of the order of 2×10^7 K would radiate 10^{38} ergs/sec, essentially with a black-body spectrum, mainly at X-ray wavelengths. Subsequent studies of the cooling of neutron stars indicated that such an object with a surface temperature of 2×10^7 K would have an internal temperature near 10^9 K, and would quickly lose most of its thermal energy through neutrino processes. As a consequence, it would cool too rapidly to be of interest. Some doubts remain, however, concerning

L. Gratton (ed.), Non-Solar X- and Gamma-Ray Astronomy, 208–215. *All Rights Reserved*

the correctness of these cooling calculations. As has been pointed out by several authors it is not unlikely that a large part of the body of a neutron star may be made of superconductive and superfluid matter. This could have important effects, both on the specific heat of the matter and on the rates of the neutrino processes (Ginzburg, 1969). In addition, the cooling calculations presuppose that the internal thermal energy is the only source of energy that need be considered. However, it appears to be likely that the magnetic and pulsational energy may be comparable to or larger than $10^{50\pm1}$ ergs. The slow dissipation of magnetic energy would occur mostly in the outer shell of the star, especially if the interior were superconductive and the fraction of the energy going into neutrinos might be kept comparatively low because the interior would not be very hot. Detailed calculations to check this point quantitatively are in progress. Thus, although at the moment no X-ray sources are known in which there is reason to believe that black-body radiation is dominant, it may be premature to exclude this process altogether.

3. Supernova Shells

The next three mechanisms all relate to supernova remnants. Five such remnants with an age less than 1000 years are known (SN 1006, Crab Nebula SN 1054, Tycho SN 1572, Kepler SN 1604 and the strong radio source Cas A which appears to have originated in an unobserved supernova event around 1700). Not much is known about SN 1006, although a radio source identification has been suggested. The Crab Nebula (at 1.5 kpc), Tycho's supernova (at 3–5 kpc) and Cas A (at 3–4 kpc) have all been identified as X-ray sources, while Kepler's supernova probably is so distant (5–10 kpc) that it would be undetectable if it radiated at the same power level as the others. It thus appears likely that most young supernova remnants (there may be 20 such objects with ages below 1000 years in the Galaxy) are X-ray sources. So far, no convincing X-ray source identifications with older supernova remnants like the Cygnus Loop have been made. Most supernova remnants appear to have initial expansion velocities of the general order of 10000 km/sec (except for the Crab Nebula, with 1500 km/sec), but there is controversy as to the total initial masses and initial energies involved. Estimates have been made ranging between 0.1 and 10 solar masses and between a few times 10^{49} and 10^{52} ergs.

The most direct way in which X-rays may be generated in a supernova remnant is by the interaction between the expanding shell and the interstellar (or circumstellar) medium. A strong shock will separate the compressed gas from the undisturbed gas; a density jump of a factor 4 and a temperature $T \sim \frac{1}{8} m_{\mathrm{p}} V^2/k$ (in the case of hydrogen, with m_{p} the proton mass, k the Boltzmann constant and V the shock velocity) are expected at the shock. Cooling effects are slow at 10^9 K (corresponding to $V \simeq 10^9$ cm/sec) and much of the radiation would come from gas at a temperature not much below this value. The medium would be optically thin to X-rays and consequently a flat spectrum is expected. This is at variance with the spectral information available for Cas A and Tycho's object (Gorenstein *et al.*, this volume p. 134). Also for the Crab

Nebula, where the temperature would be lower, a spectral fit with this model seems impossible. Moreover, in all cases, the interstellar density that is needed to account for the observed intensities is quite high; in the case of the Crab Nebula 70 cm^{-3} (Heiles, 1964), a value almost a factor 100 larger than appears probable on other grounds.

4. Synchrotron Radiation

The prime candidate for this mechanism is the Crab Nebula. A discussion of the motions of the filaments which were measured by Trimble (1968) leads to a most probable distance of 1500 pc (see Appendix). Much is known about the spectrum of the object (Figure 1) from radio to X-ray wavelengths, the main uncertainty being whether the radio spectrum turns up beyond 10000 Mc/sec or not. For the moment we consider the measurements that do not show this rise as the more reliable. In

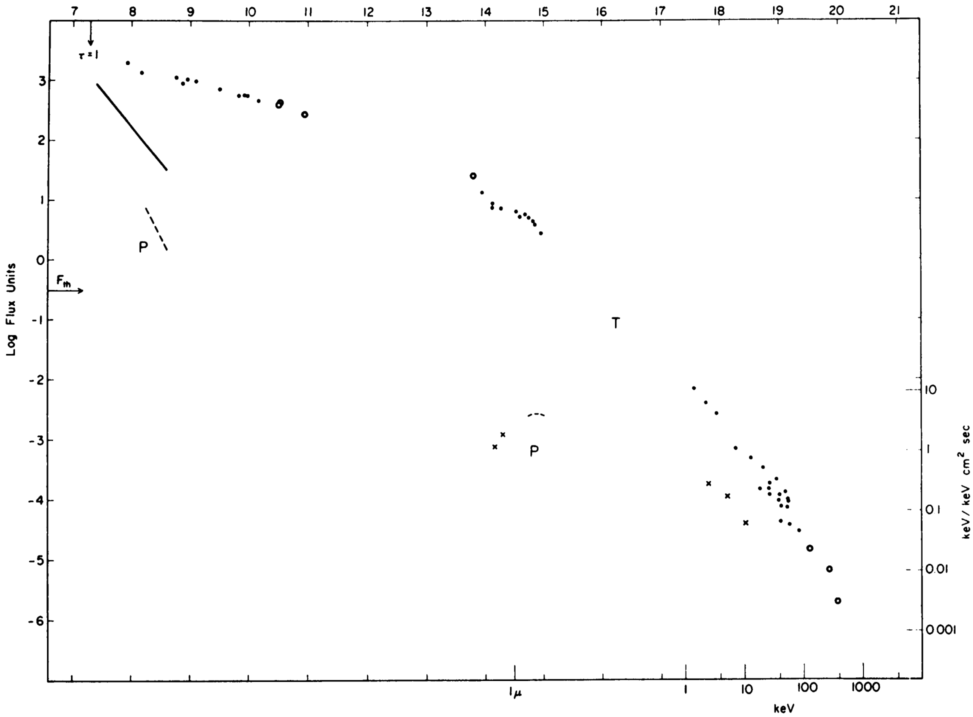

Fig. 1. The Spectrum of the Crab Nebula. Filled and open (for less reliable data) circles represent intensities from the Nebula as a whole. An upper limit to the far ultraviolet radiation inferred from the ionization equilibrium in the filaments is indicated by T. The filamentary shell becomes optically thick at the frequency labelled $\tau = 1$, while the thermal flux from the shell at higher frequencies (but with $h\nu \ll kT$) is indicated by F_{th}. The solid line represents the spectrum of the small-diameter component discovered by Hewish; and the dashed lines and crosses represent the time averaged spectrum of the pulsar. The scale on the left is (logarithmically) in flux units (1 f.u. $= 10^{-26}$ W m^{-2} Hz^{-1}), while the scale at the top gives the log ν, with the frequency ν in Hz. For the X-ray region the intensities are also shown in keV/keV cm^2 sec. and the photon energy in keV. All optical and infrared data have been corrected for $1^{\mathrm{m}}.5$ interstellar absorption in the visual.

plotting the optical and infrared points a correction for interstellar absorption and reddening must be made. The spectrum shown in Figure 1 has been corrected for a visual absorption of $1^{\mathrm{m}}.5$, based on the available measurements of colors of nearby stars. The optical spectrum shows a distinct wiggle and it is clear that a simple smooth synchrotron spectrum does not provide a good fit in detail. If the interstellar absorption correction is arbitrarily reduced to $0^{\mathrm{m}}.75$, the optical spectrum becomes smoother, but also steeper, and a fit to the X-ray data is no longer possible. Thus, although most of the spectrum can be represented by a smoothly varying function, some discrepancies remain which require further study. Because different parts of the nebula have somewhat different spectra, it is important that measurements be done at all wavelengths with good spatial resolution. On integrating the spectrum of Figure 1, we obtain a total luminosity of 9×10^{37} ergs/sec for the whole nebula, most of the total arising from the spectral region between the optical and X-ray wavelengths. It can be shown (Woltjer, 1958) that the electrons responsible for the optical radiation must have lost too much energy to be a possible relic from the original supernova event, but must have been accelerated more recently. More direct evidence for continuing activity in the nebula comes from the 'light ripples' discovered by Baade and discussed recently by Scargle (1969). These are ridges of light moving in the central region of the Nebula at speeds of up to 0.1 or 0.2 *c*. At least in some cases the light appears to be polarized in such a way as to indicate propagation transverse to the local magnetic field. Most probably these ripples are hydromagnetic waves produced in the neighborhood of the pulsar. Unless the amplitudes of the waves are very large, the propagation velocities indicate that the density of non-relativistic gas in the central parts of the nebula must be quite low (~ 0.1 cm^{-3}).

The discovery of a pulsar in the Crab Nebula has greatly contributed to the development of a consistent picture, in that it almost certainly represents the basic source of energy for the Nebula. Although the radiation mechanism has not yet been determined, it appears probable that pulsars are rotating neutron stars with a strong magnetic field. If the rotation period is identified with the period of the pulsar, then the observed increase of the period corresponds to a slowing down of the rotation and a decrease of the rotational energy. If we consider a 1-solar-mass neutron star of 10 km radius rotating as a solid body with a 30 ms period and with the period increasing at the observed rate, the energy loss is 2×10^{38} ergs/sec.

As we pointed out at the Fourth Texas Symposium, the assumption of solid body rotation may be doubtful. The braking effects act on the outside of the object and the inside could be expected to rotate faster than the outside, especially if superconductive effects exclude the magnetic field from part of the interior. It is interesting to note that differential rotation tends to be unstable in many cases. These instabilities will cause a variable coupling between the core and the mantle of the object and can be expected to cause decreases in period like the one observed in Vela pulsar. Because reliable viscosity and conductivity coefficients are not available, it is difficult to explore the situation more quantitatively.

If we assume that at least a good part of the neutron star rotates with more or less the same angular velocity, the figure of 2×10^{38} ergs/sec should not be changed too much. Of course, different neutron star models and masses can be considered, and thus this figure is uncertain by a factor of 3 at least. Nevertheless, it is remarkably close to the input needed to maintain the nebular radiation.

Can the rotational energy of a neutron star be efficiently converted into energetic particles? The answer seems to be positive. Pacini (1967) and Gunn and Ostriker (1969) argue that a rotating neutron star with an inclined dipolar field will radiate low frequency electromagnetic waves and that these waves will accelerate particles with high efficiency. Goldreich and Julian (1969) have shown that the electric fields present around a rotating magnetic neutron star – even in the axisymmetric case – will accelerate particles and set up current systems which may result in substantial magnetic fields. They make the very interesting suggestion that the magnetic field of the Crab Nebula may be understood this way. In both approaches a surface field of a few times 10^{12} Gauss is implied by the slowing down of the pulsar, while electrons may attain energies of 10^{13} eV or more, which is adequate to account for the hard X-rays observed in the Crab Nebula.

In a qualitative fashion, a combination of synchrotron losses, diffusion of particles and field inhomogeneities (as evidenced by the light ripples) acting on a power law injection spectrum, can explain the nebular spectrum. We know that different parts of the nebula have somewhat different spectra. To make reliable models it would be of great value to have not only total intensities, but also intensity distributions at different wavelengths. In particular, one would like to know the diameter of the nebula in hard X-rays, which would give direct information on the relative rates of particle diffusion and radiative losses rather close to the pulsar.

The radio spectra and X-ray spectra of Cas A and Tycho's supernova remnant may each be fitted with one power-law type spectrum. The absence of an easily noticeable optical continuum is understandable in view of the smallness of the expected brightness and (at least in Cas A) the very large interstellar absorption in the galactic plane. The main problem with a synchrotron interpretation is that the spectra should steepen at higher energies because of radiative losses. A possible way to avoid this would be a very rapid diffusion of particles out of these remnants.

5. Hot Gas Inside the Supernova Remnant

Sartori and Morrison (1967) have proposed that the X-rays of the Crab Nebula (and the same could apply to the other supernova remnants) arise in a gas heated by the activity in the remnant. Typical parameters would be a solar mass of gas with a density of 100 particles per cubic centimeter at temperatures ranging from 10^7 K to 10^9 K. The strongest argument in favor of this idea was that it seemed difficult to accelerate relativistic particles without producing a large amount of heat. This argument, however, has lost much of its force by the discovery of the pulsar and of possible mechanisms by which a pulsar can accelerate relativistic particles with high efficiency. The high density of the gas would not allow the fast propagation of the light ripples in the Crab Nebula and consequently a rather complex distribution of the gas would be needed. At the same time the hotter parts of the gas would have a considerable pressure and their containment would pose serious problems.

6. Hot Gas Surrounding Neutron Star / 7. Hot Gas Surrounding White Dwarfs

Generally these two possibilities, which have been considered by Shklovsky (1967) and Burbidge and Prendergast (1968), among others, have been considered in the framework of double star evolution, with one component of the double star evolving and transferring mass to the degenerate component. Mass falling onto a neutron star or white dwarf may become quite hot. If a small piece of matter without angular momentum falls freely onto a white dwarf and thermalizes its kinetic energy, a temperature of 10^9 K could be reached. The real situation is much more complex, however. Angular momentum is quite important, while in a steady flow the pressure effects also need be considered. As a consequence the infalling gas may lose a good part of its energy by radiating at temperatures well below the maximum value. Nevertheless the results of Burbidge and Prendergast in particular are quite promising in that they show that in plausible flows, temperatures of the order of 10^7 K may be obtained even with white dwarfs.

The main difficulty for models of this type is that despite extensive spectroscopic studies no specific evidence for binary motion has been found in Sco X. However, it is not clear at the moment how effectively one may 'hide' the binary characteristics by the gas streams in the system. Perhaps one will have to consider an alternative mode of producing a hot corona around a white dwarf or neutron star.

From the observational side some support is available for the idea that a hot gas cloud with white-dwarf type dimensions is responsible for the X-rays of Sco X. Such a gas cloud would be optically thin at X-ray wavelengths. The 1–10 keV spectral observations indicate a temperature of 5×10^7 K on the average, although the harder X-rays would probably require a higher temperature. If we adopt 500 pc for the distance we find from the X-ray intensities $N_e^2 V = 1.4 \times 10^{60}$. Neugebauer *et al.* (1969) find that the infrared data follow about a Rayleigh-Jeans type law which indicates the source to be optically thick. For a spherical source of radius R they obtain from the infrared intensities and the Rayleigh-Jeans law, $R^2 T = 3 \times 10^{25}$. Neugebauer *et al.* subsequently make the assumption that the cloud is spherical and uniform in its physical properties. From these results it then follows that $R = 8 \times 10^8$ cm and $N_e = 2.7 \times 10^{16}$ cm^{-3}. Neugebauer *et al.* observe that the optical depth for electron scattering is large ($\sim$14 from center to front) while the total optical depth for absorption (taking into account the path length increase caused by electron scattering) is about 6 at 10000 Å and 2.5 at 3000 Å, which possibly is a bit high in view of the flattening of the optical spectrum, but of the right order of magnitude.

It is very striking that the dimensions of the X-ray source turn out to be comparable to those of white dwarfs. A more probable model then is a shell of hot gas around a white dwarf. Taking, for example, a white dwarf radius R^* of 7×10^8 cm we would have, with the outer radius of the shell again equal to 8×10^8 cm, $N_e = 4.8 \times 10^{16}$ cm^{-3}. The optical depth of the shell in electron scattering now is only about 4 and the absorption optical depth more nearly unity or less at optical wavelengths.

Clearly models of this type are overly simplistic. We hardly can expect the gas to be isothermal either near the interface with the white dwarf atmosphere or towards the outside. The main effect of this might be to somewhat increase the outer radius of the shell.

In the optical spectra of Sco X emission lines are seen (N II, O III, H, etc.). The spectroscopic evidence indicates that the density is rather high. The same conclusion is inferred from the low degree of ionization in the strong ultraviolet radiation field of Sco X. If we take the temperature of the gas to be 30000 K the density has to exceed 10^{11} cm^{-3} for gas at 10^{10} cm from the center. Of course at greater distances lower densities become possible.

Radio emission has been detected at 6 cm with a flux per unit frequency interval about equal to that at optical wavelengths. If the radiation were thermal it would have to come from a fairly large region ($R \approx 10^{14}$ cm for $T = 10^4$ K if the medium were optically thick, and larger otherwise). In the optically thin case both the radio emission and the Hβ emission are proportional to N_e^2 integrated over the source, and it is easily verified that the Hβ emission which corresponds to the observed radio emission exceeds the observed Hβ emission by a factor of 20. Optical depth effects will increase the discrepancy. This appears to imply that the radio source is nonthermal. The Parkes data at 11 cm, reported at this symposium, appear to confirm this conclusion. If the radio source is indeed Sco X, the interesting result would be that a thermal X-ray source would be associated with a nonthermal radio source, and consequently with the acceleration of fast particles.

Appendix

THE DISTANCE OF THE CRAB NEBULA

The extensive material on proper motions and radial velocities obtained by Trimble (1968) provides a basis for determining the distance of the Crab Nebula. The basic method of equating the tangential velocities derived from proper motions at the edge of the Nebula with the radial velocities observed near the center meets the following difficulties:

(1) The systematic motion of the Nebula as a whole should be corrected for.

(2) The velocity field does not resemble that of a smoothly expanding shell very well: considerable irregularities are present.

(3) The Nebula is not axisymmetric and some assumption as to the three-dimensional shape must be made.

If we disregard these three difficulties and consider the Nebula in the mean as an expanding spherical shell, it appears most reasonable to simply equate the 'largest' proper motion observed with the 'largest' radial velocity. By arranging the motions in order of absolute magnitude and taking the 'largest' motion equal to the average

TABLE I

Distance determinations for the Crab Nebula

Velocities used	'Mean largest' proper motion	'Mean largest' radial velocities	Distance
All	0″.203/yr	1284 km/sec	1340 pc
Major axis	0″.189/yr	1247 km/sec	1390 pc
Minor axis	0″.157/yr	1247 km/sec	1680 pc

Adopted distance 1500 parsec

of the third through tenth largest values, we obtain the first entry of Table I.

Next we consider only filaments whose position angle (as seen from the center) differs less than 30° from that of the major axis. Near each end of the major axis we take the 2d–5th largest proper motions and average the eight values. Similarly we take the average of the 2d-5th largest positive – and negative – radial velocities. The resulting average largest motions should be independent of the systematic velocity of the Nebula. By equating the radial and tangential motions, the second entry in Table I is obtained; and by applying the same method of filaments near the minor axis, the third entry. On the basis of the results of Table I, we adopt a value of 1500 parsec for the distance of the Crab Nebula.

Acknowledgement

This research was supported in part under Contract AF 49 (638) 1358.

References

Angel, J. R. P.: 1969, to be published.
Burbidge, G. R. and Prendergast, K. H.: 1968, *Astrophys. J. (Letters)* **151**, L83.
Ginzburg, V. L.: 1969, *Nature*, to be published.
Goldreich, P. and Julian, W. H.: 1969, *Astrophys. J.*, to be published.
Gunn, J. E. and Ostriker, J. P.: 1969, *Nature* **221**, 454.
Heiles, C.: 1964, *Astrophys. J.* **140**, 470.
Neugebauer, G., Oke, J. B., Becklin, E., and Garmire, G.: 1969, *Astrophys. J.* **155**, 1.
Pacini, F.: 1967, *Nature* **216**, 567.
Sartori, L. and Morrison, P.: 1967, *Astrophys. J.* **150**, 385.
Scargle, J. D.: 1969, *Astrophys. J.* **156**, 401.
Shklovsky, I. S.: 1967, *Astrophys. J. (Letters)* **148**, L1.
Trimble, V. L.: 1968, *Astron. J.* **73**, 535.
Woltjer, L.: 1958, *Bull. Astron. Inst. Neth.* **14**, 39.